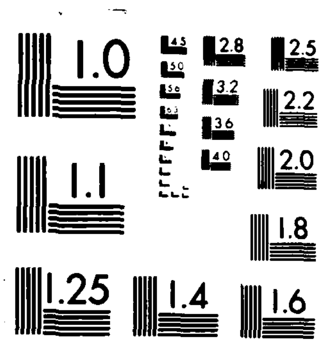
AD-A147 481 NONCONTACT PHOTO-THERMAL PROBE-BEAM DEFLECTION MEASUREMENT OF THERMAL DIF..(U) IBM RESEARCH LAB SAN JOSE CA J C LOULERGUE ET AL. 17 OCT 84 RJ-4472 (48260) 1/1

UNCLASSIFIED N00014-83-C-0170 F/G 20/5 NL

END
DATE
FILMED
12-84
DTIC



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

RJ 4472 (48260) 10/17/84
Physics

(12)

Research Report

NONCONTACT PHOTO-THERMAL PROBE-BEAM DEFLECTION MEASUREMENT OF THERMAL DIFFUSIVITY IN AN UNCONFINED HOT GAS

J. C. Loulergue
A. C. Tam

IBM Research Laboratory
San Jose, California 95193

~~LIMITED DISTRIBUTION NOTICE~~

~~This report has been submitted for publication outside of IBM and will probably be copyrighted if accepted for publication. It has been issued as a Research Report for early dissemination of its contents. In view of the transfer of copyright to the outside publisher, its distribution outside of IBM prior to publication should be limited to peer communications and specific requests. After outside publication, requests should be filled only by reprints or legally obtained copies of the article (e.g., payment of royalties).~~

IBM Research Division
Yorktown Heights, New York • San Jose, California • Zurich, Switzerland

Copies may be requested from:
IBM Thomas J. Watson Research Center
Distribution Services
Post Office Box 218
Yorktown Heights, New York 10598

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER 13	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Noncontact photo-thermal probe-beam deflection measurement of thermal diffusivity in an unconfined hot gas.		5. TYPE OF REPORT & PERIOD COVERED Technical Report
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) J.C. Loulergue A.C. Tam		8. CONTRACT OR GRANT NUMBER(s) N00014-83-C-0170
9. PERFORMING ORGANIZATION NAME AND ADDRESS International Business Machines, Corp. 5600 Cottle Rd., San Jose, CA 95193		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS NR633-844
11. CONTROLLING OFFICE NAME AND ADDRESS Office of Naval Research 800 N. Quincy St., Arlington, VA 22217		12. REPORT DATE 10/18/84
		13. NUMBER OF PAGES 11
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report)
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

This document has been approved for public release and sale; its distribution is unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

To be published in Applied Physics Letters

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Photo-thermal, thermal diffusivity gas, laser application, temperature, flame diagnostics.

-carbon dioxide

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A pulsed CO_2 laser beam is used to produce a transient thermal refractive-index-gradient in nitrogen gas doped with trace amounts of absorbing Freon 12 at temperatures from 25°C to 425°C. The diffusion of this gradient is probed by a continuous HeNe laser beam parallel but displaced from the pulsed beam. The observed deflection signal agrees well with the theory of Jacson et al. (1981), and signal.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-LF-014-6601

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

965 · IBM · 18

965 · IBM · 18

OFFICE OF NAVAL RESEARCH

Contract N00014-83-C0170

Task No. 633-844

TECHNICAL REPORT No. 13

Noncontact photo-thermal probe-beam defectionmeasurement
of thermal diffusivity in an unconfined hot gas.

By

J. C. Loulergue

A. C. Tam

IBM Research Laboratory
San Jose, California

965 · IBM · 18

965 · IBM · 18

TECHNICAL REPORT DISTRIBUTION LIST, GEN

	No.		No.
Office of Naval Research Attn: Code 413 800 N. Quincy Street Arlington, VA 22217	2	Naval Ocean Systems Center Attn. Technical Library San Diego, California 92152	1
Dr. Harold E. Guard Dept. of the Navy Office of Naval Research Arlington, VA 22217	1	Naval Weapons Center Attn: Dr. A. B. Amster Chemistry Division China Lake, California 93555	1
Commander, Naval Air Systems Command Attn: Code 310C (H. Rosenwasser) Washington, DC 20360	1	Scientific Advisior Commandant of the Marine Corps Code RD-1 Washington, DC 30280	1
Naval Civil Engineering Laboratory Attn: Dr. R. W. Drisko Port Hueneme, CA 93401	1	Dean William Tolles Naval Postgraduate School Monterey, CA 93940	1
Superintendent Chemistry Division, Code 6100 Naval Research Laboratory Washington, DC 20375	1	U. S. Army Research Office Attn: CRD-AA-IP P. O. Box 12211 Research Triangle Park, NC 27709	1
Defense Technical Information Center Building 5, Cameron Station Alexandria, Virginia 22314	12	Mr. Vincent Schaper DTNSRDC Code 2830 Annapolis, Maryland 21402	1
DTNSRDC Attn: Dr. G. Bosmajian Applied Chemistry Division Annapolis, Maryland 21401	1	Mr. John Boyle Materials Branch Naval Ship Engineering Center Philadelphia, Pennsylvania 19112	1
Naval Ocean Systems Center Attn: Dr. S. Yamamoto Marine Sciences Division San Diego, California 91232	1	Mr. A. M. Anzalone Administrative Librarian PLASTEC/ARRADCOM Bldg. 3401 Dover, New Jersey 07801	1

965 - IBM - 18

DL/413/83/01
633/413-2

TECHNICAL REPORT DISTRIBUTION LIST, 633

Dr. Henry Freiser
Chemistry Department
University of Arizona
Tucson, AZ 85721

Dr. Gregory D. Botsaris
Department of Chemical Engineering
Tufts University
Medford, MASS 02155

Dr. J. H. Hargis
Department of Chemistry
Auburn University
Auburn, ALA 36849

Dr. Ronald S. Sheinson
Code 6180
Naval Research Laboratory
Washington, DC 20375

Dr. Edward J. Poziomek
Chief, Research Division
Chemical Research and
Development Center
ATTN: DRDAR-CLB
Aberdeen Proving Ground, MD 21010

Dr. Lynn Jarvis
Code 6170
Naval Research Laboratory
Washington, DC 20375

Dr. Richard Hollins
Code 385
Naval Weapons Center
China Lake, CA 93555

Dr. Christie G. Enke
Department of Chemistry
Michigan State University
East Lansing, MICH 48824

Dr. Timothy L. Rose
EIC Laboratories, Inc.
111 Chapel Street
Newton, Massachusetts 02158

RJ 4472 (48260) 10/17/84
Physics

NONCONTACT PHOTO-THERMAL PROBE-BEAM DEFLECTION MEASUREMENT OF THERMAL DIFFUSIVITY IN AN UNCONFINED HOT GAS

J. C. Loulergue*
A. C. Tam

IBM Research Laboratory
San Jose, California 95193

ABSTRACT: A pulsed CO_2 laser beam is used to produce a transient thermal refractive-index-gradient in nitrogen gas doped with trace amounts of absorbing Freon 12 at temperatures from 25°C to 425°C. The diffusion of this gradient is probed by a continuous HeNe laser beam parallel but displaced from the pulsed beam. The observed deflection signal agrees well with the theory of Jackson *et al.* (1981), and thermal diffusivity or gas temperature can be derived from the signal.

---

*On leave from Institut d' Optique Théorique et Appliquee, Centre Universitaire d' Orsay, B. P. No. 43, 91406 Orsay Cedex, France.

The Photo-Thermal Probe-beam Deflection (PTPD) method developed by Boccara and co-workers[1-5] has gained much attention recently as a noncontact spectroscopic measurement tool in gases as well as in condensed matter. PTPD relies on the generation of a thermal Refractive-Index-Gradient (RIG) in or near a sample due to the absorption of a "pump" beam, and the detection of this RIG by a continuous probe beam. In most PTPD work,[1-8] the pump beam is a continuous modulated laser beam obtained by chopping at tens of Hz, and the probe beam deflection is modulated correspondingly. However, Rose *et al.*[9] have recently used a pulsed laser for PTPD spectroscopy in a flame. The advantages of using pulsed laser are that much higher power is available and also measurements related to a transient thermal RIG can be made.

We have made a first experimental investigation of the evolution of the transient thermal RIG produced by a pump laser pulse and detected by a spatially separated probe beam. Unlike the previous PTPD investigations which are mainly spectroscopic, we show here that thermal diffusivity D or gas temperature can be obtained by analyzing the time-dependent PTPD signal shape. This provides a new method for noncontact monitoring of temperature or material composition that affect D. The present experiment is designed to measure the thermal RIG in an unconfined hot gas to mimic an open flame. It should be noted that a pulsed laser can also generate an acoustic RIG in a flame observable with probe-beam deflection.[10]

Our experimental apparatus is indicated in Fig. 1. The gas cell is made from a block of aluminum alloy of dimension about 5 cm × 4 cm × 1.8 cm. Suitable cavities are made in the aluminum block to allow cartridge heaters to be inserted for heating of the gas. Two open windows of dimension 2 mm × 5 mm allow the entrance and exit of the laser beams. A slow stream of nitrogen with 0.11% Freon 12 (pre-mixed gas from

Matheson) flows into the aluminum cell. The purpose of the low concentration of Freon is to provide some weak absorption of the pump beam, which is a CO_2 laser beam at 10.834 μm, with pulse width 150 μsec and peak power 50 Watt at 30 Hz repetition rate. The gas flow rate is smaller than 10^{-2} cc/sec to ensure that the gas temperature in the measurement chamber is at the cell temperature. Both CO_2 laser beam and the probe HeNe laser beam are focused at the center of the cell by a ZnSe lens of 125 mm focal length and a glass lens of 250 mm focal length, respectively. The two laser beams are parallel and in the same horizontal plane. They are separated by a displacement r that is adjustable by an accurate translation platform carrying the HeNe laser and its focusing lens and the photodetector. The cell, the CO_2 laser beam with the ZnSe focusing lens and the KRS-5 beam splitter are fixed in position. The horizontal geometry of the two laser beams is used to minimize any effects due to flow or convection, as indicated in Sell's work.[8] The HeNe laser beam emerging from the cell is transmitted through a quartz plate (which blocks the CO_2 laser beam); after some suitable propagation distance, the defocused HeNe laser beam is incident on a small aperture which is positioned asymmetrically with respect to the probe beam cross section. This aperture is used[11,12] to convert a probe deflection into an intensity variation, which is monitored by a photodiode-amplifer assembly (UDT model 600). The photodiode signal S(r,t) is digitized by a Tektronix 7854 oscilloscope, which accumulates the signal and transmits it to a personal computer (IBM PC) via an IEEE 488 bus. The IBM PC stores the signal, prints it on a matrix printer, as well as generates theoretical signals to compare with the experimental ones.

The theoretical PTPD signal shape S(r,t) can be derived according to the work of Jackson *et al.*[4] In their Eq. (28), they show that a pulsed laser beam of Gaussian radius

a, energy E_0 and pulse duration t_0 produces a temperature gradient $\partial T/\partial r$ in an infinite medium with weak absorption coefficient α given by

$$\frac{\partial T}{\partial r} = \frac{-\alpha E_0}{2\pi k t_0 r} = \left[\exp\left(\frac{-2r^2}{a^2 + 8Dt}\right) - \exp\left(\frac{-2r^2}{a^2 + 8D(t - t_0)}\right)\right] \tag{1}$$

for $t>t_0$. Here t is the time measured from the starting of the laser pulse and k is the thermal conductivity of the medium. The corresponding[11] probe defection angle $\phi(r,t)$ is

$$\phi(r,t) \approx \frac{\ell}{n_0} \frac{\partial n}{\partial T} \frac{\partial T(r,t)}{\partial r} \tag{2}$$

where ℓ the interaction path length ($\approx$1.8 cm in our experiment), n_0 is the ambient refractive index of the gas and $\partial n/\partial T$ is the temperature coefficient of the refractive index. The observed signal at the photodiode is (for small deflection angles)

$$S(r,t) = GI_p'(r_1)L\phi(r,t) \tag{3}$$

where G is a constant depending on the photodiode sensitivity and gain, $I_p'(r_1)$ is the lateral spatial derivative of the probe beam intensity distribution at the aperture position r_1 and L is the "lever arm" of the probe beam (*i.e.*, distance from the cell center to the aperture and is about 22 cm in our experiment). Combining Eqs. (1)-(3), we have

$$S(r,t) = K\,\frac{\alpha E_0}{r}\left[\exp\left(\frac{-2r^2}{a^2 + 8Dt}\right) - \exp\left(\frac{-2r^2}{a^2 + 8D(t-t_0)}\right)\right] \tag{4}$$

where

$$K = -\frac{1}{2\pi k t_0}\,\frac{\ell}{n_0}\,\frac{\partial n}{\partial T}\,GI_p'(r_1)L \tag{5}$$

is independent of t and r. Equation (4) is valid for $t>t_0$, and is the basis of pulsed PTPD measurement. It shows that α can be measured as a function of excitation wavelength, as

done in previous PTPD measurements.[1-9] It also shows that D can be measured by fitting the observed signal shape S(r,t) to the form in the square bracket in Eq. (4), as done in the present work.

Our signal observed on the oscilloscope for $x=0.126$ cm and cell temperature $T_c=25°C$ is shown in Fig. 2. Here, we see that the photodiode signal has a fast component and a slow component. The fast component is not appreciably delayed from the laser pulse on the scope time scale of 1 ms/div; this component is due to the acoustic RIG probe-beam deflection effect,[10-12] which occurs at a time delay of about 4.2 μsec from the laser pulse for a sound speed of 3×10^4 cm/sec. The signal variation after the initial sharp spike is due to the thermal RIG and follows the shape indicated in Eq. (4).

The signals averaged for 100 laser shots stored in the computer for two cell temperatures T_c are shown in Fig. 3. The signal magnitude is observed to decrease as temperature increases, in accordance with Eq. (2), since $\partial n/\partial T$ goes as T^{-2} for an ideal gas. We clearly see that the signal peak moves to earlier times as temperature increases, indicating that thermal diffusivity D increases with temperature. By fitting Eq. (4) to the observed signals, we can obtain the theoretical signals shown in Fig. 3 with the values of D_{fit} as indicated. These theoretical curves are calculated with the following parameters: laser pulse width=150 μsec, excitation beam Gaussian radius=0.07 cm, and separation between excitation and probe beam=0.105 cm. In reality, the excitation beam is not Gaussian but has annular structures, so that the theoretical fits are not perfect.

Table 1 indicates some of our experimental results for a range of cell temperature T_c. The fitted diffusivity values D_{fit} increases very substantially with temperature. The dependence of thermal diffusivity on temperature for N_2 at 1 atmosphere has been

extensively measured in the literature,[13-17] generally with the use of wires or probes inserted into the gas. Using the diffusivity data listed by Rutherford *et al.*[13] (which is consistant with data from other workers), we can convert the measured D_{fit} in Table 1 into corresponding averaged gas temperature $\overline{T}_g$. We see that $\overline{T}_g$ is generally somewhat cooler than the cell body temperature T_c. This is probably due to cooling effects occurring at the windows.

In conclusion, we have demonstrated a noncontact pulsed PTPD measurement in an unconfined hot gas for monitoring thermal diffusivity or the related temperature. The observed signal shape S(r,t) agrees well with the theoretical form of Jackson *et al.*[4] Such a nonintrusive method should be valuable for measurements *in situ* in open medium like flames or in other hostile environments.

ACKNOWLEDGMENTS

This work is supported in part by the Office of Naval Research. We thank Dr. A. C. Boccara and Dr. D. Fournier for very helpful discussions.

Table 1

Cell Temperature, Fitted Thermal Diffusivity From the Signal and the Corresponding Average Gas Temperature Based on Literature (Ref. 13)

$\bar{T}_c$(°C)	D_{fit} (cm^2/sec)	$\bar{T}_g$(°C)
25	0.21	25
48	0.230	42
79	0.258	64
131	0.32	110
155	0.369	141
222	0.47	205
233	0.498	221
312	0.574	267
423	0.810	386

REFERENCES

1. A. C. Boccara, D. Fournier and J. Badoz, *Appl. Phys Lett.* **36**, 130 (1980).
2. D. Fournier, A. C. Boccara, N. M. Amer and R. Gerlach, *Appl. Phys. Lett.* **37**, 519 (1980).
3. A. C. Boccara, D. Fournier, W. Jackson and N. M. Amer, *Opt. Lett.* **5**, 377 (1980).
4. W. B. Jackson, N. M. Amer, A. C. Boccara and D. Fournier, *Appl. Opt.* **20**, 1333 (1981).
5. O. Benchikh, D. Fournier, A. C. Boccara and J. Teixeira, "Photothermal Measurement of Supercooled Water Thermal Conductivity," preprint.
6. M. A. Olmstead, N. M. Amer, S. Kohn, D. Fournier and A. C. Boccara, *Appl Phys* **A32**, 141 (1983).
7. M. A. Olmstead and N. M. Amer, *Phys. Rev. Lett.* **52**, 1148 (1984).
8. J. A. Sell, *Appl. Opt.* **23**, 1586 (1984).
9. A. Rose, J. D. Pyrum, C. Muzny, G. J. Salamo and R. Gupta, *Appl. Opt.* **21**, 2663 (1982).
10. W. Zapka, P. Poknowsky and A. C. Tam, *Opt. Lett.* **7**, 477 (1982).
11. B. Sullivan and A. C. Tam, *J. Acoust. Soc. Am.* **75**, 437 (1984).
12. A. C. Tam and W. P. Leung, *Phys. Rev. Lett.* **53**, 560 (1984).
13. W. M. Rutherford, W. J. Roos and K. J. Kaminski, *J. Chem. Phys.* **50**, 5359 (1969).
14. Y. S. Touloukian, P. E. Liley and S. C. Saxena, "Thermal Conductivity: Nonmetallic Liquids and Gases," Plenum, N. Y., 1970.
15. S. H. P. Chen and S. C. Saxena, *High Temp. Sci.* **5**, 206 (1973).
16. J. W. Haarman, AIP Conference Proc. No. 11, Edited by J. Kestin, American Instit. of Phys. N. Y., 1973, p. 193.
17. R. M. Thomson, *J. Phys. D: Appl. Phys.* **11**, 2509 (1978).

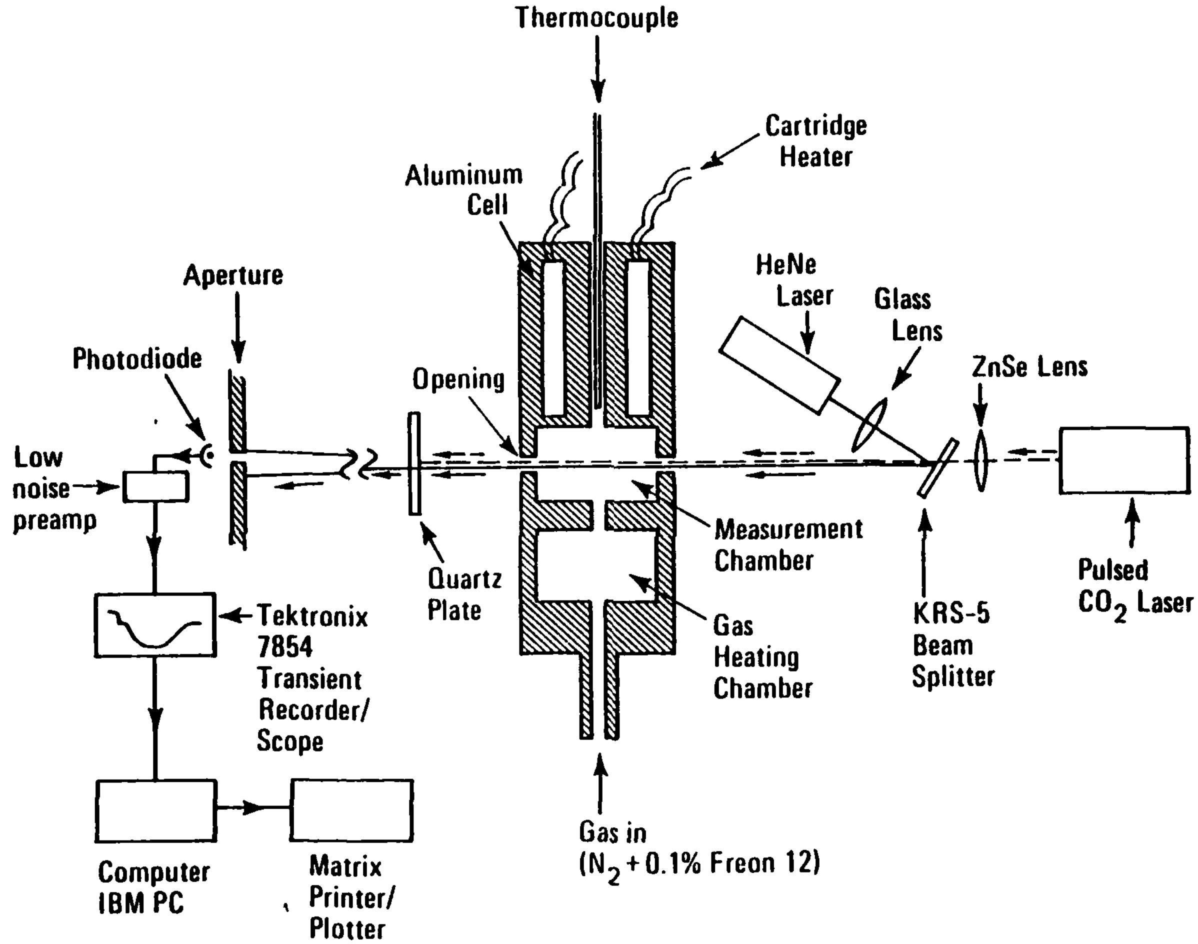


Figure 1. Experimental arrangement.

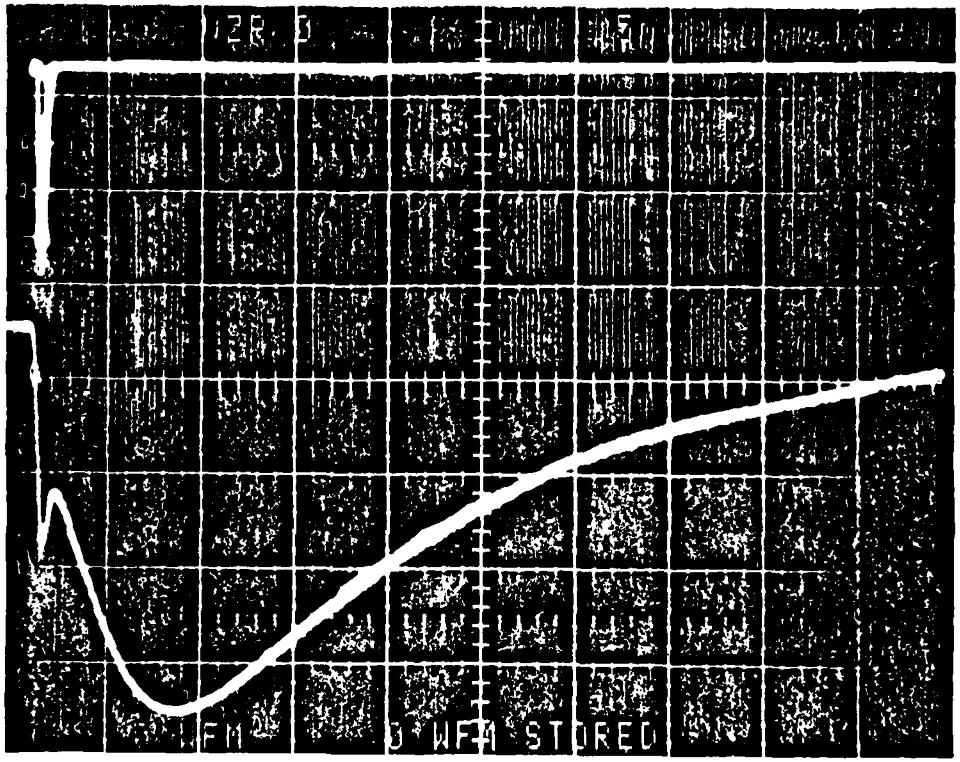


Figure 2. The upper oscilloscope trace shows the CO_2 laser pulse shape, and the lower trace shows the observed photothermal deflection signal for N_2 at 25°C for beam separation r=0.105 cm. Horizontal scale is 2 ms/div.

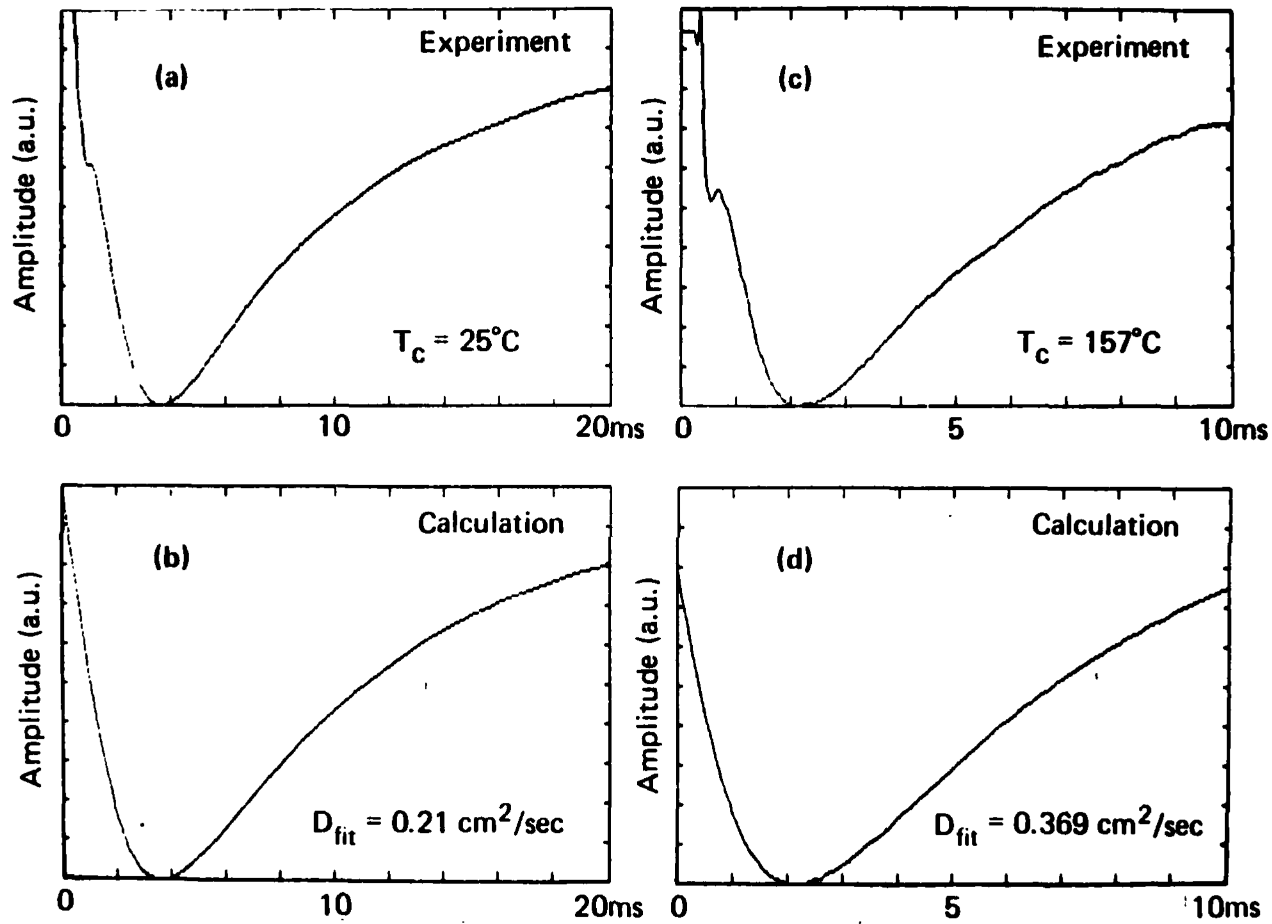


Figure 3. Observed photothermal deflection signal at two different temperatures. (a) T_c=25°, (c) T_c=157°c for beam separation r=0.105 cm, as compared to the theoretical deflection signals using the fitted values of thermal diffusivity (b) D_{fit}=0.21 cm^2/sec, (d) D_{fit}=0.369 cm^2/sec.

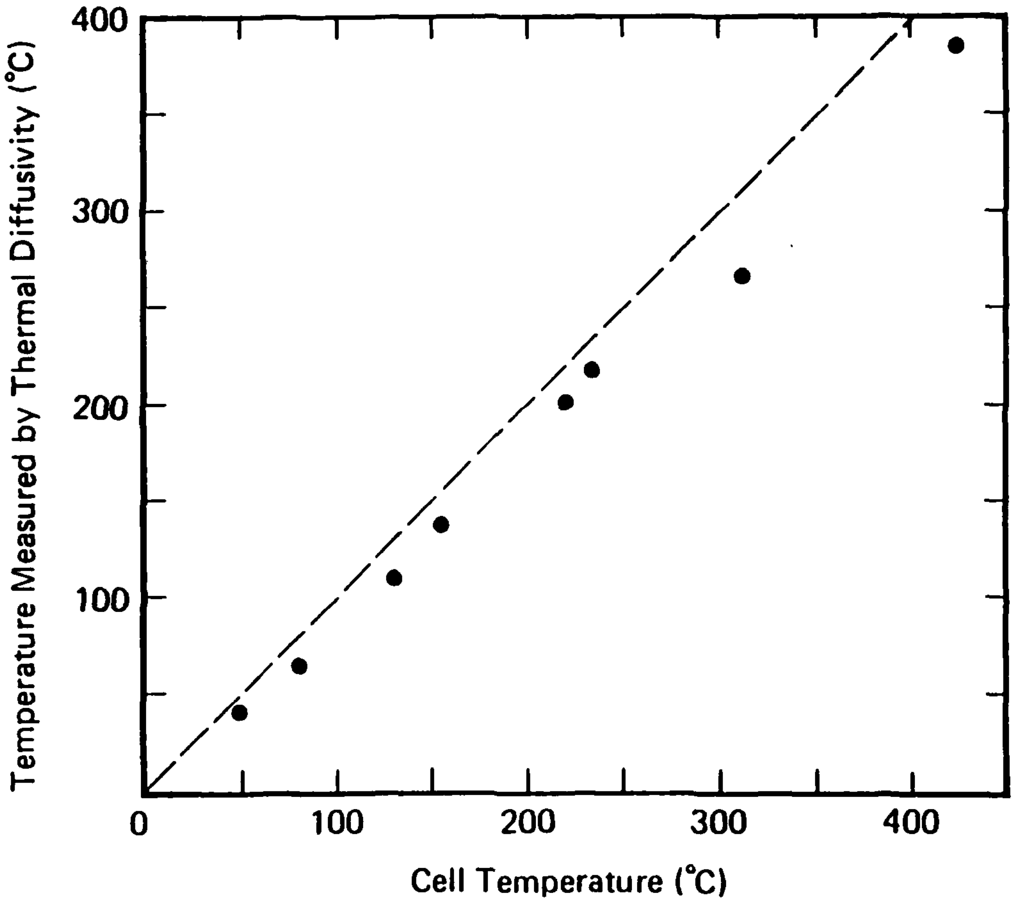


Figure 4. Measure "mean" gas temperature ($\overline{T}_g$) based on the values of D_{fit} as a function of cell temperature T_c given by a thermocouple. The dotted line indicates the case when the gas column being monitored is of uniform temperature at T_c.